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Radio Evidence for Solar Corpuscular Emission

BY

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Fort Davis, Texas

Contract No. AF19(628)-2370

Project No. 7649

Task No. 764906

SCIENTIFIC REPORT NO. 5

July 1964

Prepared for
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

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RADIO EVIDENCE FOR SOLAR CORPUSCULAR EMISSION

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Abstract—This paper reviews the relation of solar radio bursts of spectral type IV to the ejection of relativistic and sub-relativistic solar particles; the relation of bursts of types II and IV to the ejection of solar plasma; and radar evidence for quiet solar streaming. Ejection of relativistic and sub-relativistic particles by flares is virtually always accompanied by type-IV radio bursts. The minimum Sun-Earth travel time for these particles is about 20 min. Ejection of plasma from flares accompanied by bursts of types II and IV is considered in terms of subsequent geomagnetic effects. Type IV bursts are highly associated with geomagnetic storms and type II bursts have a small but significant association. The Sun-Earth travel time for the storm plasma is generally 36–48 hr. Type II Bursts may possibly be identified with passage through the corona of a large amplitude shock wave, which then propagates outwards through the interplanetary plasma, causing a geomagnetic sudden commencement when it reaches the earth. The presence of type IV radiation may be indicative of the amount of material transported behind the shock front. Radar observations of the solar corona indicate that at a height of approximately 350,000 km above the photosphere there is a net outward flow of matter at a velocity of about 16 km/sec. This velocity is consistent with Parker's hydrodynamic theory, for coronal temperatures of the order of 10^6 °K.

1. INTRODUCTION

In this paper we review radio-physical data obtained since 1957 concerning the quiet streaming and occasional violent ejection of matter from the Sun. The paper is concerned with direct radio observations of the solar atmosphere, rather than ionospheric radio information (such as ionosonde, VHF forward scatter and riometer observations) except insofar as the latter provides information of the time of arrival of solar corpuscular streams at the terrestrial atmosphere. It should be remarked at the outset that radio emissions and radar echoes from the solar plasma are determined by the motions of electrons. Radio evidence concerning the outward streaming or violent ejection of protons and heavier particles is thus of a secondary or derived nature. The radio observations do, however, provide substantive evidence concerning the movement of large scale disturbances outward through the solar corona and also give information about the acceleration of particles in flare regions.

Flares that eject high-energy nucleons and solar plasmas are usually of large optical area and intensity and are generally accompanied by complex radio bursts. The total flare energy may be $> 10^{32}$ ergs⁽¹⁾, although energy radiated in the radio spectrum is probably only of the order 10^{24} ergs. Such flares are often accompanied by an abrupt increase in optical activity indicating a sudden expulsion of corpuscular matter and shock waves. This activity generally coincides with the onset of the radio bursts and has been called the flash phase⁽²⁾, flare puffs⁽³⁾ or the explosive phase⁽⁴⁾. The processes by which particles are accelerated in the flare region have been ascribed to the Fermi mechanism, the pinch effect at magnetically neutral points, electrical discharge and linear acceleration (recent summaries of flare theories and acceleration processes are given by Ellison⁽⁵⁾, de Jager⁽⁶⁾ and Smith and Smith⁽⁷⁾).

With regard to solar radio bursts, the present analysis is confined mainly to bursts of spectral types II (slow-drift) and IV (continuum), since existing evidence suggests that these are the types of radio bursts most significantly associated with the ejection of solar

corpuscular material into the interplanetary plasma. We do not deal with type I (noise-storm) and type III (fast-drift) radio bursts. The former are generated in the corona above large active sunspot areas and indicate the presence of "R-centers", which at central meridian passage have been shown by Denisse⁽⁸⁾ to be correlated, in a general manner, with terrestrial magnetic activity. Type III bursts may be generated by jets of high-energy particles, traveling outward through the corona at velocities of the order of $0.5c$, but as yet there is no proven association between these radio bursts and the ejection of particles from the solar atmosphere into interplanetary space. The radio energy emitted by type III bursts is often limited, so that if the bursts are generated by superthermal particles the energy density in the jet could be quite small. During the next sunspot maximum it should be of much interest to determine, from counters borne on satellites or solar probes, whether minor streams are in fact ejected by the flares that generate type III bursts.

Type II bursts are generated in the solar corona by a disturbance moving outward from a flare at a velocity of the order $1000\text{--}1500\text{ km/sec}$ ^(9,10). This disturbance probably has the nature of a magnetohydrodynamic shock front, which may also be carrying corpuscular material and magnetic fields with it. It is possible that particles are accelerated in the shock front itself^(11,12).

Type IV bursts are believed to be generated by relativistic electrons, of energy $0.5\text{--}5\text{ MeV}$, constrained by magnetic fields in the solar atmosphere to radiate by the synchrotron mechanism. Since nearly all observed cases of very-high-energy nucleon emission are associated with type IV bursts, it is generally assumed that the flare mechanism which accelerates electrons to relativistic velocities also accelerates the heavier nucleons to sub-relativistic or relativistic energies. The very-high-energy nucleons escape directly from the solar plasma, whereas the electrons are temporarily retained by magnetic fields in the chromosphere and corona. On many occasions, however, the radiating center of the type IV burst is subsequently observed to move outward through the solar corona at velocities of about $1000\text{--}5000\text{ km/sec}$, to distances >5 solar radii^(13,14).

For convenience, we may divide flare-initiated solar corpuscular streams into three main types. Referring to the maximum energies of protons incident at the Earth, we have: streams containing protons of energies $>1\text{ BeV}$, which cause cosmic-ray ground-level events (GLE); streams containing protons of energies $10\text{--}300\text{ MeV}$, which cause ionospheric polar-cap absorption (PCA); and plasma clouds containing protons of energy $<10\text{ keV}$, which produce aurorae and geomagnetic storms. Streams in these distinct energy ranges may be regarded as superimposed on a more or less continuous outward streaming of particles, the "solar wind", with protons in the energy range $<1\text{ keV}$. We draw attention to the fact, however, that these energy divisions are arbitrary, that the streams often overlap in time, and that there may well be a continuous gradation in particle energy between the various categories. For example, Bryant, Cline, Desai and McDonald⁽¹⁵⁾ discuss evidence concerning the trapping of 15 MeV protons within geomagnetic storm plasma; and Gregory⁽¹⁶⁾ offers evidence that solar protons with energies $>1\text{ MeV}$ were incident at the Earth for at least 167 days during the year 1960.

In Section 2 we examine the relation of flares with radio bursts of type IV to the emission of the relativistic particles that give cosmic-ray ground-level events and the sub-relativistic particles that give ionospheric polar-cap absorption. In Section 3 we examine the relation of the type II and type IV bursts to subsequent geomagnetic storms and assess the time delays between the radio bursts and the arrival of the plasma clouds at the Earth. In Section 4 we review radar evidence for quiet outward streaming of electrons and compare

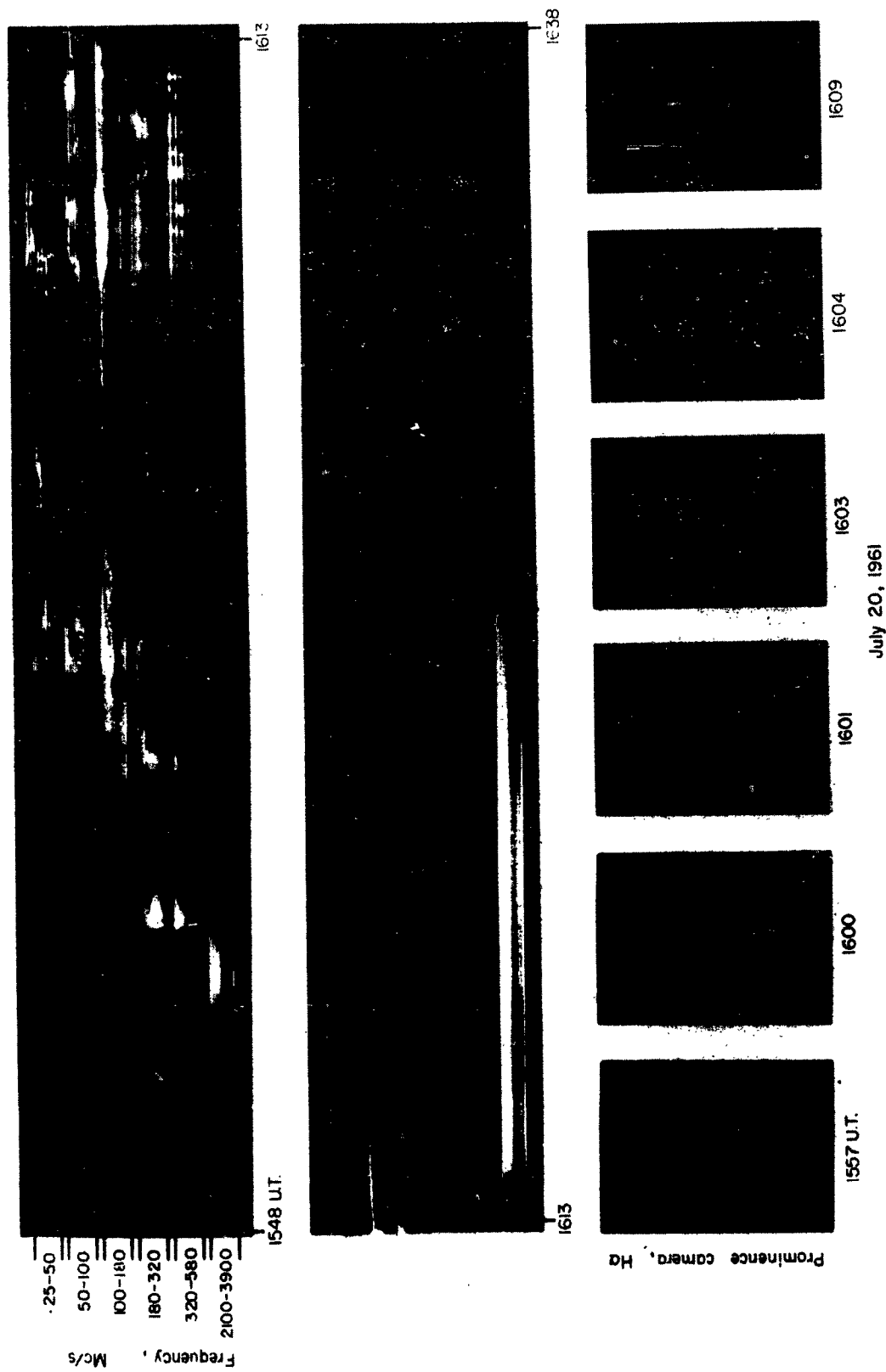


FIG. 1. RECORDS OF A COMPLEX TYPE II-IV SOLAR RADIO BURST AND ACCOMPANYING SPRAY PROMINENCE THAT OCCURRED ON 20 JULY 1961. The flare coordinates were 06 S 90 W. High-energy nucleons from the flare first reached the Earth at 1620 UT. (Optical data courtesy Sacramento Peak Observatory.)

the radar data with the streaming velocities predicted from existing theory on the solar wind⁽¹⁷⁻¹⁹⁾.

2. EMISSION OF RELATIVISTIC AND SUB-RELATIVISTIC PARTICLES

Boischot and Denisse⁽²⁰⁾ suggested that flares emitting relativistic (>1 BeV) solar protons, giving ground-level cosmic-ray increases, were probably all accompanied by type IV radio bursts. They further proposed that the acceleration mechanism generating the relativistic electrons responsible for the type IV bursts simultaneously brought heavier particles to relativistic energies. After the discovery of the sub-relativistic (10–500 MeV) solar protons that cause ionospheric polar cap absorption, several authors noted the close correlation of type IV bursts, especially when associated with class 3 and 3+ flares, with the ejection of these slightly lower-energy particles⁽²¹⁻²³⁾. Most of the radio bursts in fact have complex spectra (Fig. 1) but the appearance of a type IV component is apparently mandatory if particles in the relativistic or sub-relativistic energy ranges are to be emitted.

In this section, we briefly re-examine certain aspects of the relation between solar radio bursts of spectral type IV and high-energy (GLE and PCA) particle emission from the Sun, during the period 1957–1961: namely, the heliographic asymmetry, as viewed from the Earth, of flares emitting such particles; and the minimum Sun–Earth travel time of the particles, as a function of flare longitude from central meridian. We then summarize certain criteria relating the energy and frequency range of type IV bursts to subsequent GLE and PCA events.

2.1 Observational data

For the present analysis we have compiled a new list of solar high-energy particle events, as observed at the Earth. The sources for this list were earlier tables compiled by various observers and discussions of individual events that are to be found in the literature. Included were data based on riometer records, ionospheric f_{min} analysis, VHF forward scatter, vertical-incidence back-scatter, balloon, rocket and satellite observations, and neutron monitor records. The detection of high-energy particles ejected from the Sun, particularly with methods involving the secondary effects in the ionosphere, is often inaccurate with regard to starting time. Reported onset times often differ by three or four hours. Furthermore, terrestrial magnetic storm activity may cause “false” polar-cap absorption resulting from a lowering of cutoff rigidities⁽²⁴⁾.

Ambiguities in flare association with particle emission result partly from incomplete daily flare coverage, and partly from the fact that the only known criteria for distinguishing a flare emitting high-energy particles are optical importance and type IV radio activity. Some observers have reported delay times from flare start to arrival of high-energy particles at the Earth of up to two days^(25,26). Some of these long delay times probably result from incomplete observations, but in certain cases it is possible that the high-energy particles were trapped in or temporarily stored in the magnetic field of a slow-travelling plasma cloud. For example, observations with the satellite Explorer XII have directly shown 15 MeV protons to be trapped in such a plasma cloud⁽¹⁵⁾.

In this paper we shall not be concerned with questions concerning the discrete reality of GLE and PCA events listed by various observers but shall confine ourselves to events associated with type IV solar radio bursts. Such a selection tends to exclude uncertain events and those which can not be definitely associated with solar phenomena. Data concerning solar radio bursts of spectral type IV were taken from spectral observations

made at Fort Davis, Texas⁽²⁷⁾ and at Sydney, Australia⁽²⁸⁾, and the IAU Quarterly Bulletin on Solar activity for 1961; and from lists of fixed-frequency observations prepared by Pick-Gutmann⁽²⁹⁾, Obayashi and Hakura⁽³⁰⁾, Sinno⁽²⁶⁾ and Bookin⁽³¹⁾.

During the 5-year period studied, 8 definite GLE cosmic-ray increases were observed. These were all associated with type IV solar radio emission. About 50 PCA events have additionally been identified with type IV bursts.

2.2 East-west asymmetry of flares emitting high-energy particles

Figure 2 shows the heliographic positions of 59 flares that were accompanied by type IV bursts and high-energy particle emission. As has been noted by previous authors^(22,32), there is an east-west asymmetry in the heliographic distribution of these flares. In the

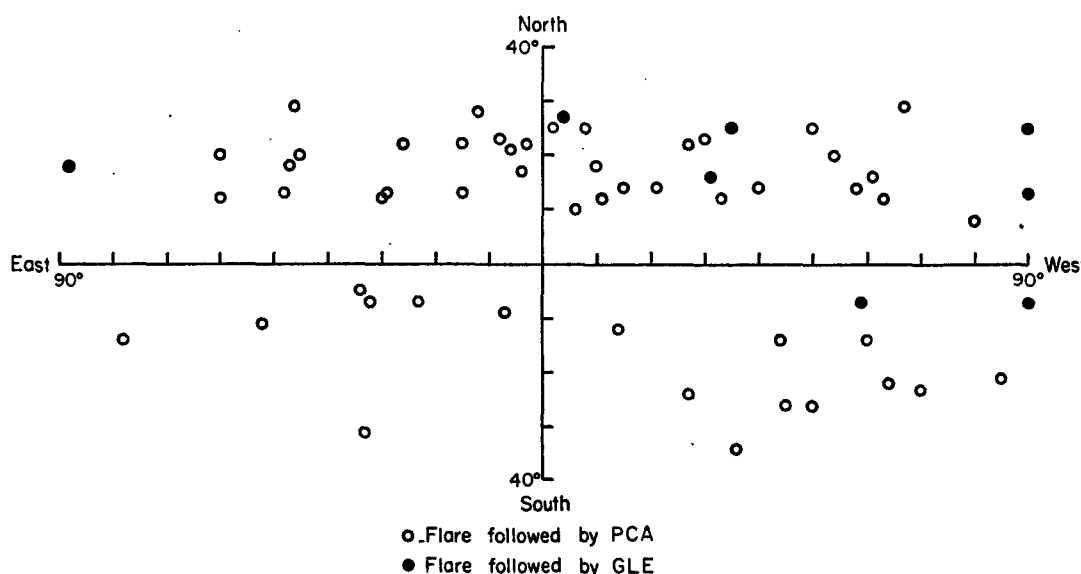


FIG. 2. HELIOGRAPHIC POSITIONS OF FLARES ASSOCIATED WITH TYPE IV RADIO BURSTS AND HIGH ENERGY PROTON EMISSION.

Note that about 70 per cent of the flares occurred in the northern solar hemisphere.

present sample, 35 flares occurred in the west and 24 in the east. Although the statistical significance of this asymmetry is low (1.4σ), we are of the opinion that the asymmetry is real, since it recurs when the data are subdivided arbitrarily.

Figure 2 includes 8 events observed by Gregory⁽¹⁶⁾ alone. There is no western dominance for these events, which are believed to be mainly of low intensity. By contrast, the flares emitting relativistic (GLE) particles show a very pronounced east-west asymmetry (7 in the west as compared with 1 in the east). The greater asymmetry for the most energetic events can be explained on the basis of a "rotating garden hose" model⁽³³⁾ of the extension of magnetic field lines from the Sun. According to this model, nucleons ejected from flares east of the solar central meridian must cross magnetic field lines to reach the Earth. Such diffusion is possible only for relatively low-energy particles which have sufficient number density to overcome the interplanetary magnetic field pressure. The high-energy particles, however, are usually guided by the interplanetary field or by a curved magnetic tongue⁽³⁴⁻³⁷⁾ and generally do not reach the Earth if they are ejected from the Sun's eastern hemisphere.

2.3 Travel times of high-energy particles

Figure 3 shows the delay time between the onset of type IV bursts and the arrival of high-energy particles at Earth, as a function of flare-longitude from central meridian. The onsets of type-IV bursts, especially in the microwave band, are known to coincide with the flash phase of the flare, which is believed to be the stage at which particles are ejected. For forty-six PCA events (not including those with accompanying GLE's) the average delay time was 117 min. This value has been corrected for the 8 min difference between solar and terrestrial time. Dividing the Sun into 3 equal-longitude zones, east, central and west, we find that the average corrected delay times were 235, 94 and 78 min,

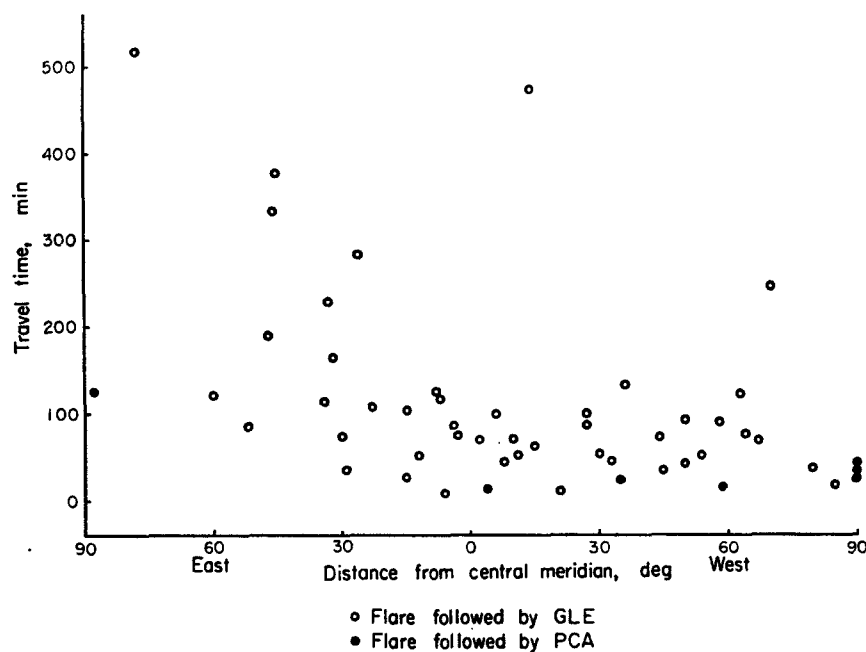


FIG. 3. MINIMUM SUN-EARTH TRAVEL TIMES OF HIGH-ENERGY SOLAR PROTONS, WITH RESPECT TO CENTRAL MERIDIAN DISTANCE OF ASSOCIATED FLARE AND TYPE IV RADIO BURST (CORRECTED FOR 8 MIN DIFFERENCE BETWEEN SOLAR AND TERRESTRIAL TIME)

respectively. Unfortunately the number of events is small and, as there were only nine events in the eastern zone, the results are by no means conclusive. As may be seen in Fig. 3, the minimum corrected delay times were about 20 min.

Obayashi and Hakura⁽²⁵⁾, Sinno⁽²⁶⁾ and others have pointed out that the delay time is greater for the eastern events than for those in the west. By contrast, Warwick and Haurwitz⁽³⁸⁾ find that the shortest average delay times are for solar flares near the central meridian (200 min), while events at $>30^\circ$ from central meridian have roughly the same delay times (300 min and 250 min for the east and west zones, respectively). The present results, shown in Fig. 3, tend to confirm the earlier results of Obayashi and Hakura.

In the case of the 8 GLE's, the starting times are known to within ± 5 min, with the exception of the strange event of July 16-17, 1959 (not included in Fig. 3), during which the arrival of particles, first detected by riometer at College, Alaska, was partially obscured by solar radio noise⁽³⁹⁾. The time delays from type IV burst to onset of the GLE are marked separately in Fig. 3 and the average corrected time was 39 min. If the solitary east limb event is omitted, this figure becomes 25 min.

2.4 Some additional points

Warwick and Haurwitz⁽³⁸⁾ and Bell⁽⁴⁰⁾ have shown that type IV bursts covering a wide wavelength range are much better related to PCA events than are bursts limited to two or three octaves of the radio spectrum. Bell⁽⁴¹⁾ also finds a significant relation between the intensity of PCA events and the duration of the preceding type IV emission in the meter band.

In the microwave band, Avignon and Pick-Gutmann⁽⁴²⁾ find that type IV bursts are generally associated with emissions of high-energy protons, if the energy of the bursts (determined from the product of their intensity and duration, at a wavelength of 10 cm) is $>10^{-17}$ Jm⁻²/cps, and if they are accompanied by a class 3 or 3⁺ flare. Similarly, Kundu⁽⁴³⁾ finds that intense broadband microwave type IV bursts having a duration >10 min and a peak intensity $>500 \times 10^{-22}$ Wm⁻²/cps over the entire wavelength band 3–30 cm are followed by PCA events in 80 per cent of cases. These criteria of Avignon and Pick-Gutmann and Kundu are essentially in agreement with the results of Warwick and Haurwitz and Bell, since bursts of such intensity in the microwave band are nearly always accompanied by strong type IV emission in the meter band. Kundu also suggests that the delay of PCA events with respect to the microwave burst is statistically dependent on both the intensity of the microwave burst and the heliographic position of the associated flare.

3. PLASMA EJECTION AT THE TIME OF SOLAR RADIO BURSTS OF SPECTRAL TYPES II AND IV

The arrival of solar plasma streams in the neighbourhood of the Earth, 24–72 hr after a solar flare, has now been directly confirmed by plasma detectors and magnetometers carried on satellites and interplanetary probes, but the available data are still meager. Historically, solar plasma streams have been detected indirectly by their effect on the terrestrial magnetic field. We use the latter method to investigate the relation of solar radio bursts to the ejection of the plasma streams during the period 1957–61. We then compare our results with those obtained by other workers who have considered various other aspects of the problem.

3.1 Mean geomagnetic conditions following solar radio bursts

We have applied the method of superposed epochs to evaluate the geomagnetic effectiveness of flares associated with type II and type IV solar radio bursts. The 24 hr ΣK_p -index has been used as the measure of magnetic field variability and superposed epoch diagrams have been prepared with type II and type IV bursts as the epoch zeros. The solar radio data were again taken from spectral observations made at Fort Davis and at Sydney. We have referred only to records taken with sweep-frequency receivers, since these data permit unambiguous spectral identification of the solar bursts. Unfortunately the available spectral data cover an average of only fourteen hours each day but this restriction is accepted in the interest of homogeneity.

Figure 4 shows the superposed epoch curve for 265 type II bursts observed during the five-year period under consideration. Geomagnetic activity increases slightly on the three days following the bursts. For a normal distribution, the peak in ΣK_p that occurs one day after burst date has a probability of chance occurrence of about 2×10^{-4} . Evidently, type II bursts are followed by a definite, though small, rise in geomagnetic activity and hence are correlated at least in time with corpuscular emission from the Sun. Figure 5 shows the superposed epoch diagram for 115 type IV bursts. In this case, the rise in

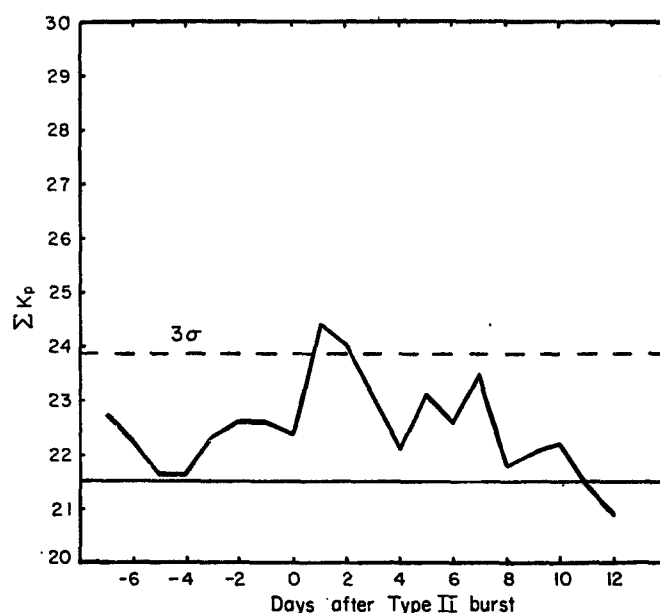


FIG. 4. SUPERPOSED EPOCH DIAGRAM OF DAILY ΣK_p FOR 265 TYPE II BURSTS. The solid horizontal line indicates the mean ΣK_p ($=21.5$) for the period 1957-61.

geomagnetic activity following the radio bursts is very large. The peak on day +2 has a probability of chance occurrence of the order of 10^{-11} , demonstrating that type IV bursts are geomagnetically very important.

An indication of the statistical significance of the results was obtained in the manner of Bell and Glazer⁽⁴⁴⁾. Deviations were measured with respect to the mean ΣK_p for 1957-61, which was 21.5. The distribution of radio bursts in time, however, is not random and we may expect the base level of geomagnetic activity to be higher when radio bursts are most frequent than at other times. Hence the superposed epoch curves will tend to be slightly above the average level of $\Sigma K_p = 21.5$.

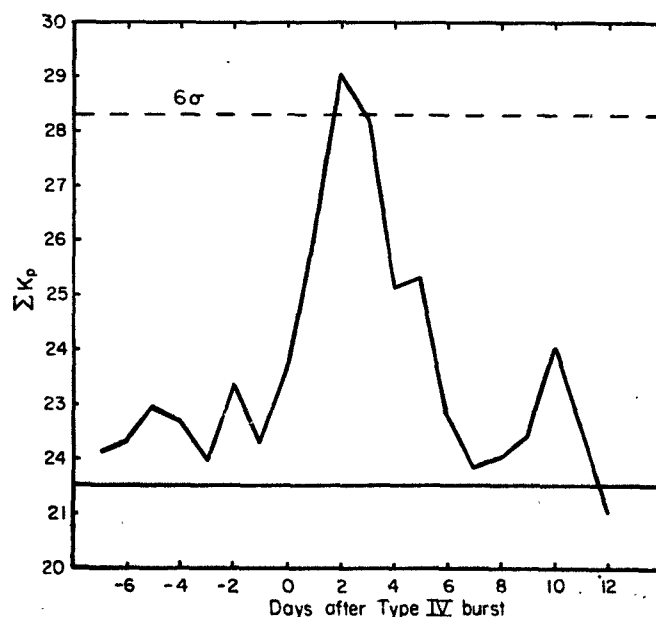


FIG. 5. SUPERPOSED EPOCH DIAGRAM OF DAILY ΣK_p FOR 115 TYPE IV BURSTS. The solid horizontal line indicates the mean ΣK_p ($=21.5$) for the period 1957-61.

Figure 6 shows that the geomagnetic significance of type IV bursts is a function of burst duration. The shortest lived bursts, duration ≤ 15 min, have no effect on the Earth's magnetic field. However, the geomagnetic importance of the type IV emission increases strikingly with burst duration. In part, this effect probably results from the fact that type IV bursts originating in flares far from the Sun's central meridian have shorter durations (since the radio emission has a relatively narrow cone of emission) and ejected particles have geometrically less chance of reaching the Earth.

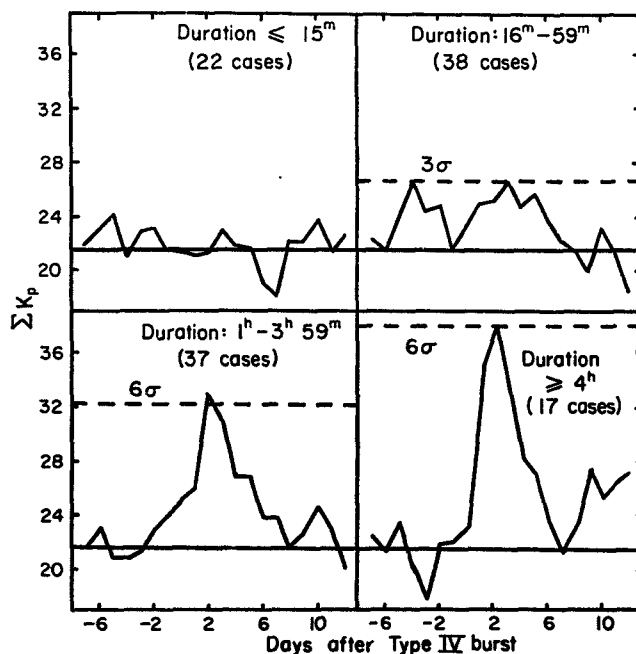


FIG. 6. SUPERPOSED EPOCH DIAGRAMS OF DAILY ΣK_p FOR TYPE IV BURSTS SUBDIVIDED BY DURATION.

The solid horizontal lines indicate the mean ΣK_p ($=21.5$) for the period 1957-61.

These results are in accord with those of other investigators. From a superposed epoch analysis based on the A_p -index, Roberts⁽⁴⁵⁾ concluded that slow-drift bursts are significantly associated with a disturbed geomagnetic field. (He found the maximum A_p -value to be about 1.5 times the quiet value. This apparently large effect results, however, from the fact that the A_p -index is a linear measure of geomagnetic activity, whereas the K_p -index used in the present analysis is on a quasi-logarithmic scale.) McLean⁽⁴⁶⁾ found a significant correlation of ten type IV continuum bursts with geomagnetic storms, but states that slow-drift bursts without associated type IV emission have slight geomagnetic importance. Similar results have also been found by Sinno and Hakura⁽⁴⁷⁾, Dodson⁽⁴⁸⁾, Kamiya and Wada⁽⁴⁹⁾ and Simon⁽⁵⁰⁾.

3.2 The delay time between solar radio bursts and geomagnetic storms

Because of the long delay times between solar flares and the onset of terrestrial magnetic storms, there is often ambiguity as to which flare or flares are responsible for the ejection of the plasma streams causing any given magnetic storm. Nevertheless, an attempt has been made to investigate the time delay between the flares with radio bursts and sudden commencement (SC) geomagnetic storms. The criterion used for selecting sudden commencements was that they should have been observed by ten or more stations⁽⁴⁰⁾. The

analysis was also checked with a more rigorous criterion—that the SCs should have occurred at the commencement of a magnetic storm, in which the K_p -indices averaged 5 for a period of at least twelve hours—without appreciable change in the results.

An SC was deemed to be associated with a solar radio burst if it occurred from 0 to 96 hr after the burst. This is a very lenient criterion and it is stressed that short time delays of, say, 0–12 hr are not necessarily considered to have any real physical significance but are included merely to avoid placing arbitrary limits on the minimum time delay. (Restrictions on the maximum time to 60 hr^(41,52), or 72 hr⁽⁴¹⁾ seem too severe in the light of

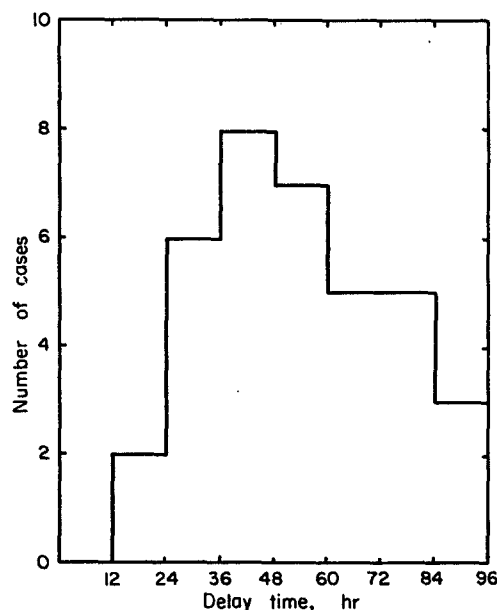


FIG. 7. FREQUENCY DISTRIBUTION OF DELAY TIMES OF SC GEOMAGNETIC STORMS FOLLOWING TYPE IV BURSTS.

the present results.) Whenever more than one SC was associated with a radio burst, or vice versa, the calculated delay times were discarded as being ambiguous. Many ambiguous events undoubtedly remain, however, through the lack of 24 hr radio spectral coverage of the Sun.

The distribution of delay times of SCs following type IV bursts (36 cases) is given in Fig. 7, which shows that geomagnetic storms had a strong tendency to occur 36–48 hr after the radio bursts. The monotonic rise and decline around the maximum at 36–48 hr clearly demonstrate the non-random nature of the SC association with type IV bursts. This result is consistent with the data of Fig. 5 which show that, following type IV bursts, there was a sudden increase in geomagnetic activity, reaching a maximum of day + 2. The mean value for the delay time was 53 hr. By contrast, type II bursts did not appear to be associated with SCs within any particular range of delay times. The mean delay time for SCs after type II bursts (49 cases) was 50 hr.

If the distribution of solar radio bursts with respect to SCs were entirely random, one would expect about 47 per cent of the bursts to be followed within four days by an SC. In fact, 55 per cent of type II bursts and 77 per cent of type IV bursts were followed by SCs. The probabilities that these degrees of association occurred by chance are about 10^{-3} and 10^{-10} , respectively.

A mean delay time of 50 hr corresponds to a rectilinear velocity of about 800 km/sec.

However, we are of the opinion that little importance should be attached to mean delay times, since plasma clouds causing geomagnetic storms are evidently ejected from the Sun with a wide range of velocities. Also, different criteria for selecting radio bursts, SCs, or magnetic storms yield delay times that differ appreciably from those given here. For example, Maxwell, Thompson, and Garmire⁽⁵¹⁾ found a mean time delay of 33 hr after type II bursts; de Feiter, Fokker, van Lohuizen and Roosen⁽⁵²⁾ found a mean time delay of 37 hr after important solar radio events observed at fixed-frequencies and thought to be predominantly of type IV; and Dodson⁽⁴⁸⁾ found a mean time interval of about 60 hr after "major early bursts".

3.3 Levels of geomagnetic activity following radio bursts

Bell⁽⁴¹⁾ has discussed in some detail the magnitude of geomagnetic activity following flares with radio bursts of types II and IV, in terms of great storms ($A_p \geq 100$ and/or $K_p \geq 9$), moderate storms ($A_p = 50-99$) and small storms ($A_p = 25-49$). The spectral radio data used in her analysis are the same as described in Section 3.1, with the exception that her analysis covers the years 1957-1960. The results are summarized in Table 1 and Fig. 8. The data show that there is a 23 per cent probability, of high statistical significance, that a great magnetic storm will occur 10-72 hr after a type IV radio burst. The probability of a great storm following a type II burst is half that for a type IV burst but is still significant. Type II bursts unaccompanied by type IV emission have only slightly more than a random probability of being followed by a great geomagnetic storm but are significantly related to small storms.

TABLE 1. PERCENTAGE OF TYPE II AND TYPE IV BURSTS FOLLOWED WITHIN THREE DAYS BY VARIOUS LEVELS OF GEOMAGNETIC ACTIVITY

Values deviating less than 2σ and more than 4σ from the random sample are designated by parentheses and bold face type, respectively (data reproduced from Bell⁽⁴¹⁾)

| Properties of events | Type II bursts | | | | Type IV bursts | | | |
|----------------------|----------------|------------------------|----------------|-------------|----------------|------------------------|----------------|-------------|
| | No. | Percentage followed by | | | No. | Percentage followed by | | |
| | | Great storm | Moderate storm | Small storm | | Great storm | Moderate storm | Small storm |
| All events | 197 | 12 | (11) | 33 | 96 | 23 | 19 | 34 |
| <30° from CM | 59 | 15 | (10) | 38 | 44 | 30 | (20) | (34) |
| 30-59° | 64 | (9) | (25) | (32) | 29 | 21 | (20) | (28) |
| ≥60° | 49 | 12 | (12) | (31) | 13 | (8) | (7) | 62 |

Bell^(40,41) also finds that, for both type II and type IV bursts, the probability that a great magnetic storm will follow is highest for bursts with the longest durations. Type IV and type II bursts occurring together have the highest probability of being followed by a great magnetic storm; and flares with type IV bursts covering a large frequency range, >2800 Mc/s to <100 Mc/s, are strikingly more successful in the production of great geomagnetic storms and PCA events than are those for which the type IV burst is limited to the microwave band.

3.4 The inverse problem: solar activity preceding geomagnetic storms

A detailed analysis of the solar activity preceding recurrent and nonrecurrent geomagnetic storms has also been carried out by Bell^(40,41) and the results are summarized in

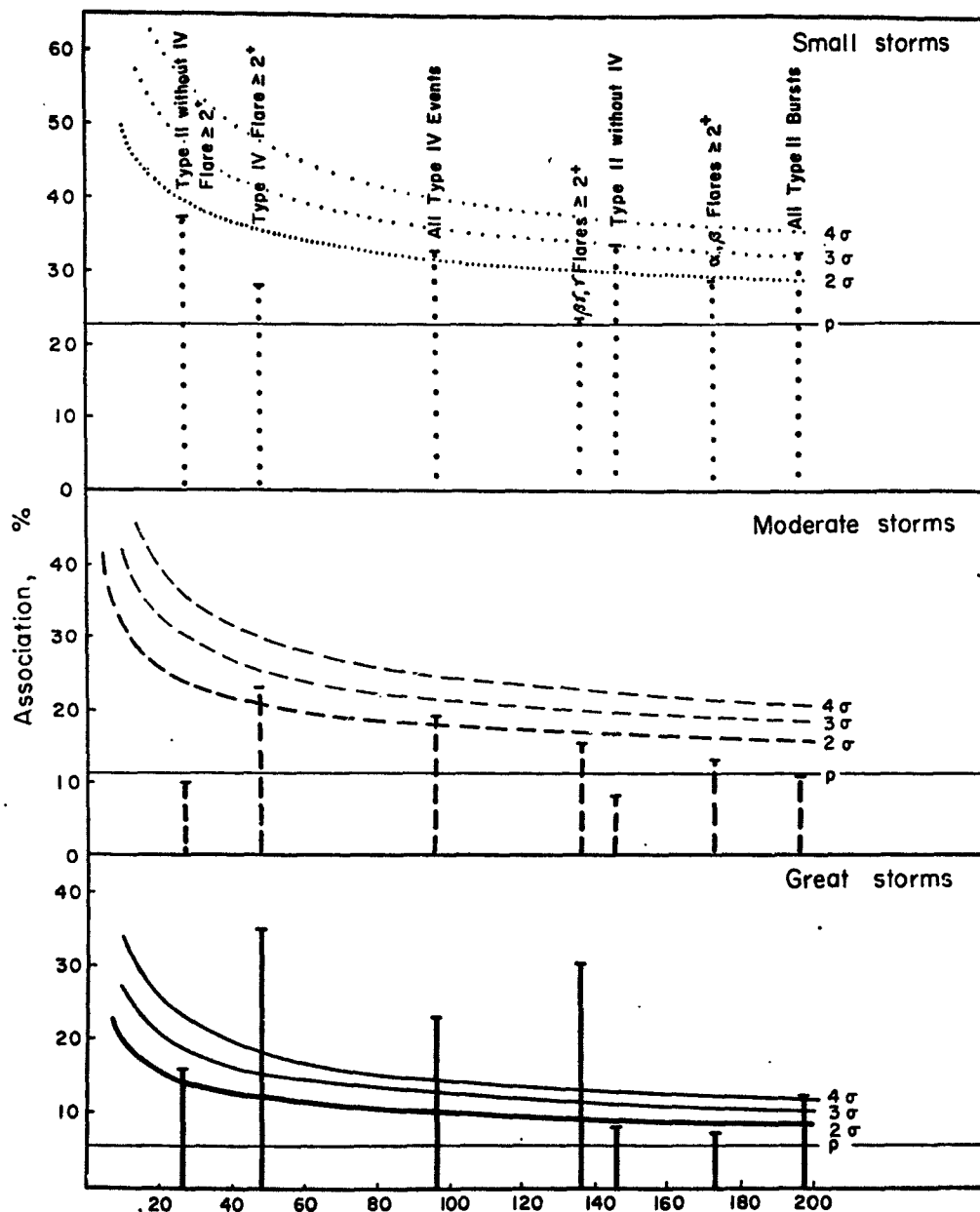


FIG. 8. ASSOCIATION OF VARIOUS ACTIVE SUN PHENOMENA WITH THREE LEVELS OF GEOMAGNETIC ACTIVITY.

The vertical lines indicate the percentage of solar events followed within three days by a great, moderate or small geomagnetic storm. The curved lines represent standard errors (σ) above the percentage (p) expected from a random sample. (Reproduced from Bell⁽⁴⁰⁾.)

Table 2. With one exception, each great storm was preceded within 3 days by at least one flare of optical importance $\geq 2+$. Just over three-fifths were preceded by type IV and by type II bursts. Since 31 per cent of the geomagnetic storms were preceded by a flare that occurred at a time when neither the Fort Davis nor the Sydney spectrum analyser was operating, it seems probable that most of the great storms considered in Table 2 were actually preceded by type IV or type II emission. The significance of the association drops sharply for moderate storms and is hardly above the number expected by chance. (The table also shows that a substantial proportion of moderate and small storms are recurrent

TABLE 2. COMPARISON OF SOLAR ACTIVITY PRECEDING RECURRENT AND NONRECURRENT GEOMAGNETIC STORMS.

Values in columns 3-5, 7, 9-11 deviating less than 2σ and more than 4σ from the random sample are designated by parentheses and bold face type, respectively. Asterisks denote values between -2σ and -4σ (data reproduced from Bell⁽⁴¹⁾)

| Storm intensity | Nonrecurrent storms | | | | | | Recurrent storms | | | | |
|-----------------|---------------------|------------------------|---------------|-----------------------|-------------|-----------|------------------|------------------------|---------------|-------------|-------------|
| | No. | Percentage preceded by | | | | | No. | Percentage preceded by | | | |
| | | Type IV burst | Type II burst | Major flare $\geq 2+$ | No activity | PCA | | Type IV burst | Type II burst | Major flare | No activity |
| Great | 20 | 65 | 65 | 100 | 0 | 75 | 6 | (50) | (50) | 83 | 17 |
| Moderate | 31 | 32 | (48) | 84 | 6 | 26 | 24 | (12) | (17) | (29) | 67 |
| Small | 73 | 26 | 48 | (49) | 32 | (14) | 40 | (12) | 17* | 22* | 68 |

and are not flare associated. Hybrid categories of geomagnetic storms (sporadic without SC and recurrent with SC) show only a random association with type IV or type II radio bursts.)

Bell also notes that 36 per cent of all type II bursts are associated with sunspot groups of complex field characteristics, as compared with 61 per cent for type IV bursts; that about 70 per cent of the flares generating type II and type IV bursts occurred in the northern solar hemisphere; and that the north-south asymmetry of solar radio bursts of types II and IV increases with burst duration.

3.5 Discussion

The statistical techniques used in this section and in the investigations of other authors are capable of demonstrating only temporal associations. Causal relations do not necessarily follow, and it is difficult to formulate even a generalized physical picture from the existing statistical information. One possibility is as follows. The present analysis indicates that type II bursts have a definite but small geomagnetic effect. Also, Bell⁽⁴¹⁾ finds that the geomagnetic effectiveness of flares with type II bursts is nearly independent of central meridian distance. These facts suggest that type II disturbances may be associated with the ejection of weak, quasi-omnidirectional beams of plasma, causing only small geomagnetic storms. By contrast, flares with type IV bursts are geomagnetically very effective but the intensity of their effect declines sharply with increasing central meridian distance. This suggests that plasma ejection at the time of type IV bursts is relatively dense and highly directional.

A second possibility arises from the suggestion⁽³⁵⁾ that the sudden commencement preceding a geomagnetic storm results from the arrival at the Earth of a shock front that has propagated through the interplanetary plasma, over the normal solar wind, at a velocity of about 1000 km/sec. It is tempting to identify the passage of such a shock front through the corona, with the generation of a type II burst. Behind the shock front one would expect to find plasma moving with a velocity slightly smaller than that of the front itself, but of the same order of magnitude. Wild⁽³³⁾ has suggested that the presence of type IV radiation may be indicative of the amount of material transported with the shock front (type II) disturbance. Thus, it may be that all type II bursts are associated with the ejection of matter from the Sun, but only those with associated type IV emission eject enough to be geomagnetically important.

4. RADAR OBSERVATIONS OF QUIET SOLAR STREAMING

In the previous sections we have considered transient corpuscular ejections associated with solar radio bursts. We now describe radar evidence for continuous outstreaming of material from the solar corona.

Solar radio echoes have been observed at the MIT Field Station, El Campo, Texas, since April 1961^(54,55). The transmitter at El Campo operates at a frequency of 38 Mc/s with a power of 500 kW, CW. The antenna beamwidths are 15° east-west and 0.75° north-south and the beam may be swung in the north-south direction by phasing. Signals

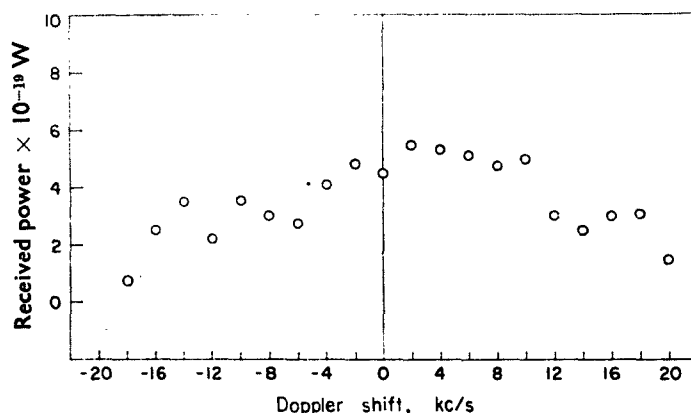


FIG. 9. DOPPLER SPECTRUM OF RADAR ECHOES FROM THE SUN, OBSERVED AT 38 Mc/s BY THE MIT FIELD STATION, EL CAMPO, TEXAS ON 16 JUNE, 1962.

(Reproduced by courtesy of Dr. J. James)

are transmitted for approximately 16 min before transit of the Sun and received for a similar period. The transmitted signal is coded in a pseudo-random sequence by frequency-shift-keying and the basic unit of keying is at present one second, giving range discrimination of about 150,000 km. The transmitted signal is cross-correlated with the returned signal, allowance being made for a round-trip group retardation delay in the corona of 1.6 sec, and the cross-correlation coefficient at a given delay time gives the echo amplitude corresponding to an appropriate range.

Solar echoes have been distinguished on about 80–90 per cent of days. The signals are apparently reflected from a height about 350,000 km above the photosphere but with a large range spread ($> 350,000$ km) and with large variations in the returned signal strength. The echoing height agrees roughly with reflection heights that would be predicted from the Baumbach–Allen model of electron density in the solar atmosphere⁽⁵⁶⁾.

A recent observation of great interest concerns the Doppler spread in the returned signals⁽⁵⁷⁾, which have a much broader spectrum than that produced by the combined motions of the Earth and the Sun. For signals returned from the Sun's equator at a height of 350,000 km, the Doppler broadening produced by solar rotation is ± 715 c/s; broadening caused by Earth rotation at the latitude of El Campo is ± 100 c/s; and the maximum shift caused by the rate of displacement along the Earth–Sun radius vector is about 130 c/s. A typical spectrum is shown in Fig. 9, from which it can be seen that the returned signals have both negative and positive Doppler shifts, > 20 kc/s, and that more energy is returned at positive frequencies than at negative. The spectral curve peaks at approximately +4 kc/s, corresponding to outward velocities of about 16 km/sec. These striking results may be interpreted in terms of radar signals being reflected from density irregularities,

which have large random motions superimposed on a net outward flow from the corona.

The expansion of the corona and the resultant solar wind have been studied theoretically by Parker⁽¹⁷⁻¹⁹⁾. Figure 10 shows the expansion velocity of the solar corona as a function of height above the photosphere, as predicted by Parker's solution of the hydrodynamic equation and the equation of continuity for an isothermal corona. The expansion velocities have been computed for coronal temperatures of 1.0 and 2.0×10^6 K. For

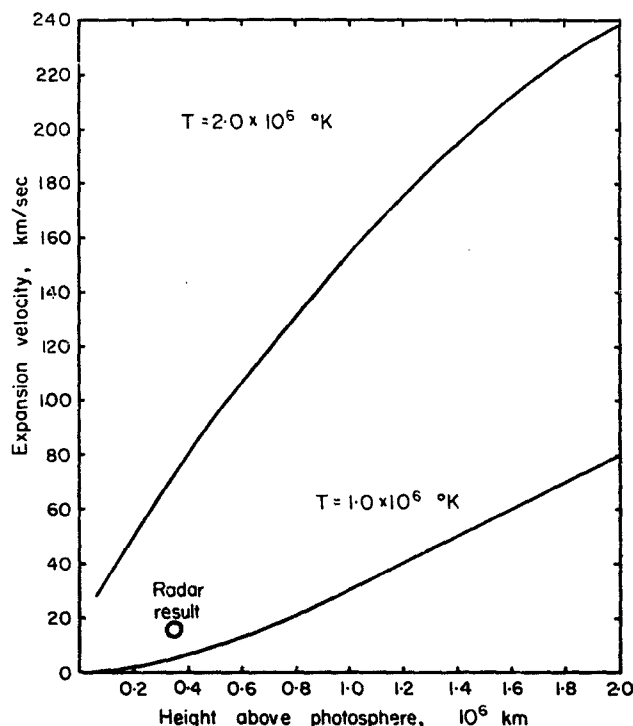


FIG. 10. EXPANSION VELOCITY OF THE SOLAR CORONA PREDICTED BY PARKER'S HYDRODYNAMIC THEORY AS A FUNCTION OF HEIGHT ABOVE THE PHOTOSPHERE FOR CORONAL TEMPERATURES OF 1.0 AND 2.0×10^6 K.

The radial velocity measured by the 38 Mc/s radar at El Campo is indicated for comparison.

$T = 1.0 \times 10^6$ K, Parker's model predicts an outward expansion velocity of about 4 km/sec at height 350,000 km. The predicted velocity for $T = 2.0 \times 10^6$ K is about 70 km/sec. Thus, for a coronal temperature of 10^6 K, Parker's hydrodynamic theory is consistent with the 16 km/sec expansion at height 350,000 km, found by the Doppler shifting of radar echoes.

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